A LOW INDUCTANCE VACUUM CONVOLUTE FOR Z-PINCH RESEARCH*

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Abstract

We have tested a novel, low inductance, vacuum convolute for driving Z-pinch loads on Proto-II (10 TW, 1.2 MV, 45 ns FWHM, and 0.125 Ω). The Proto-II vacuum section has four separate insulator stacks (1 m dia., 16 cm high) feeding four disk feeds. These disk feeds are coupled together by twelve, vertical magnetically-insulated transmission lines (MITLs) that are, in turn, convoluted into a single-disk MITL near the load. This convolute adds all of the inductance of the individual feeds in parallel, resulting in a total system inductance of 6.5 nH and short circuit currents as great as 9 MA. The vertical-to-disk convolute includes regions of poor magnetic insulation, which result in significant electron losses for the Z-pinch loads.

Introduction

Pulsed power driven Z-pinches have been used for some time as intense x-ray sources [1]. A low inductance, low impedance accelerator can efficiently couple machine electrical energy to an imploding Z-pinch load. This paper describes a self-magnetically insulated vacuum convolute which is used to minimize inductance and, hence, deliver the highest possible current to the load.

For low impedance drivers, such as Proto-II, it is very important to minimize the total inductance when driving Z-pinches. The current delivered to the load by a low impedance machine is determined, to a great extent, by the load inductance. In contrast the current on a high impedance machine is dominated by the characteristic driver impedance.

There are two basic design approaches that one can take to minimize load inductance in a multi-module machine. First, a convolute can be made in the water transmission lines to combine all of the machine energy into a single transmission line (and vacuum feed). This method has the advantage of simplicity and reliability but the total inductance is limited by the inductance of the vacuum feed. We successfully tested this concept on Proto-II and found the current limited to about 4.5 MA (9 nH diode inductance). The second approach involves vacuum convolutes. A vacuum convolute possesses the advantage that inductance, external to the convolute, is added in parallel. Thus, the vacuum convolute gives potentially lower inductance, but at the cost of complexity and potential vacuum power flow difficulties. Most vacuum convolutes contain regions of poor (or nonexistent) magnetic insulation and it is this problem that must be overcome in order to have a working vacuum feed.

One such convolute is the 'post hole' convolute developed at Sandia [2] and later used at Physics International Co. [3]. In this paper we describe experimental results from a new vacuum convolute wherein a large number of vacuum magnetically-insulated transmission lines are convoluted to a single disk feed at a small radius. Recent experiments on Proto-II, using a vertical-to-disk convolute, have demonstrated excellent power flow to short circuit loads, delivering peak currents as large as 9 MA. At this time shots using a gas puff load experience losses in the vertical-to-disk convolute which may limit the general applicability of this concept.

Experimental Description

The experiments described herein were performed on Proto-II, a 10 TW, 0.125 Ω accelerator [4]. Proto-II, with its eight modules, produces over 320 kJ of forward-going electrical energy in the water transmission lines with a voltage pulse of 45 ns full-width-at-half-maximum (FWHM). Typical first-to-last water switch spreads are 10-12 ns. The water transmission lines consist of sixteen, 2Ω triplate lines, each of which is convoluted using a standard rod crossover network into two 4Ω triplates. We maintained a constant total impedance. The water lines, now 32 triplates, feed the electrical energy into the vacuum through four independent insulator stacks (1 m in diameter).

The vacuum feed consists of four, independent disk feeds just inside the insulator stack. All four disks are immediately coupled together with twelve anode and twelve cathode vertical magnetically-insulated transmission lines (MITLs) that converge toward the center of the feed. At a radius of 10 cm, all of the anode vertical lines are attached to a single anode disk and the cathode vertical lines are attached to a cathode disk. This horizontal single disk-feed then couples the electrical energy to the Z-pinch load located on the axis of the machine. See Figs. 1 and 2 for photographs of the vacuum feed.

Machine diagnostics consist of transit-time isolated capacitive voltage monitors on each of the sixteen water transmission lines, eight capacitive voltage monitors (V-dots) (two on each insulator stack), and eight segmented Rogowski coils (two on each insulator stack). The sixteen voltage monitors on the transmission lines determined the overall machine performance: power, total energy, and module jitter. The remaining monitors gave the current and voltage at the vacuum interface. On some shots quartz piezoelectric pressure transducers and/or B-dots were fielded to measure the current reaching the load. Getting quantitative current measurements in the high current density region near the load was very difficult. In addition to the electrical diagnostics, the total radiation output from the load was a useful indication of the power flow to the gas puff load.

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14. ABSTRACT

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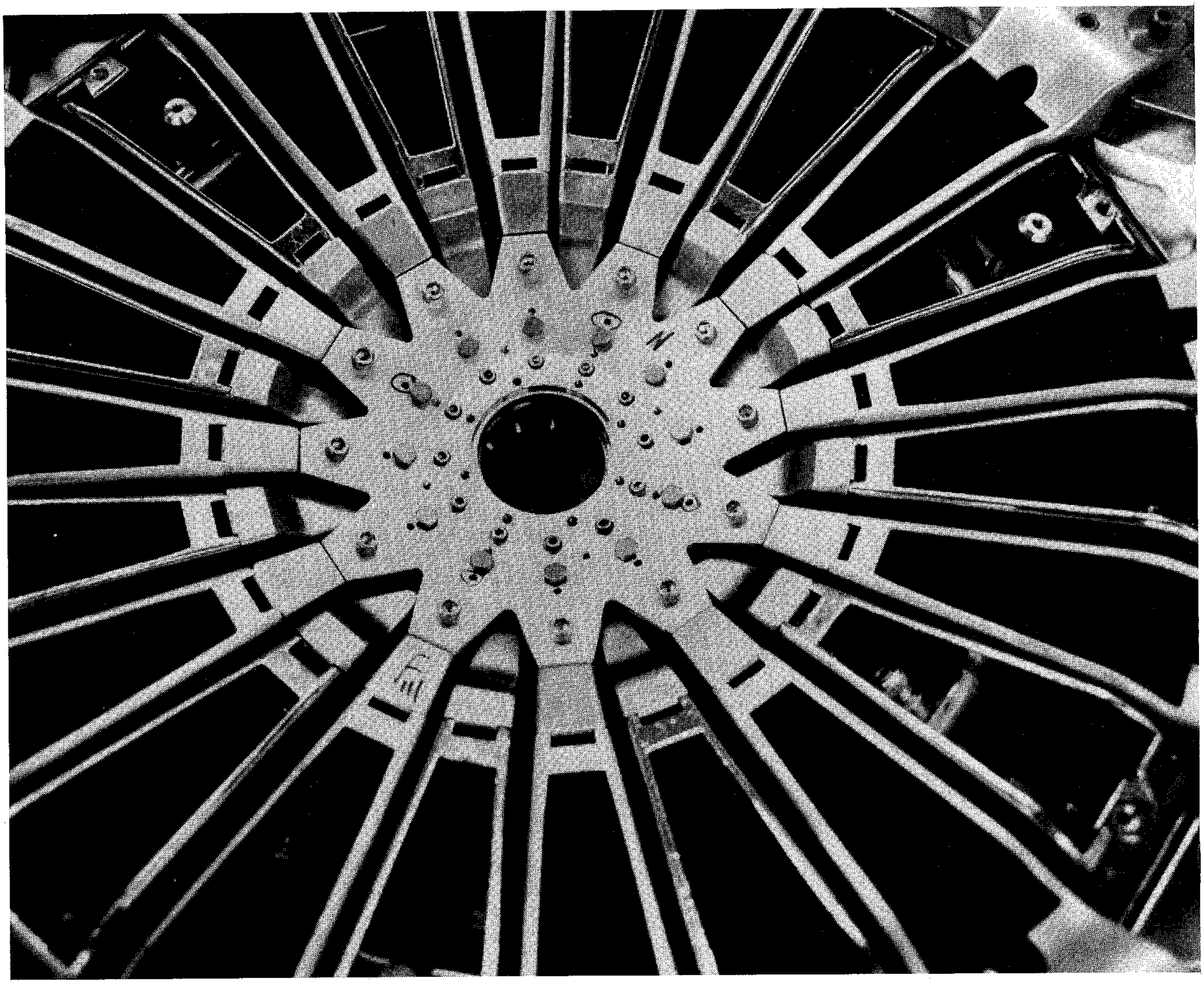

Figure 1. A view of the vertical-to-disk convolute showing the anode and cathode vertical MITLs.

Results

We were chiefly concerned with power flow problems in two areas: the vertical MITLs and the inner vertical-to-disk convolute. The vertical MITLs are not strongly self-magnetically insulated because the current per line is small, compared to the total current, and because the current does not flow uniformly across the lines. Because of these intrinsic problems, we took care to examine the cathode MITL current distribution and modify the design accordingly. Figure 3 shows the calculation of current flow in a simple vertical MITL which was fed in four locations and had a single current exit point. The local current density approaches zero in some locations. This would imply a lack of local magnetic insulation. Figures 4 and 5 show further iterations in the vertical feed design. We fabricated the initial vertical MITLs based upon the design shown in Fig. 5.

Severe electron losses in the vertical MITLs were observed in early experiments at the location on the cathode vertical lines where the upper and lower feeds join together. The losses occurred at the location on the vertical cathode MITL where the lower and upper cathode feeds came together and these losses caused heavy damage to the adjacent anodes. The design calculations failed to include sufficient current in the lower cathode feed. With a larger amount of current in the lower feed a current null point was created at the joint in the cathode MITL. These losses were, to a great extent, eliminated by removing cathode material from the loss region. Removal of cathode material serves two purposes. First, the poorly insulated parts of the cathode are not present to emit electrons. Second, the current that had been flowing at that location on the cathode is forced to flow in adjacent regions, thus improving the local magnetic insulation. Overall, several empirical iterations on the cathode MITL shape were required to nearly eliminate losses in the vertical MITLs. Later,

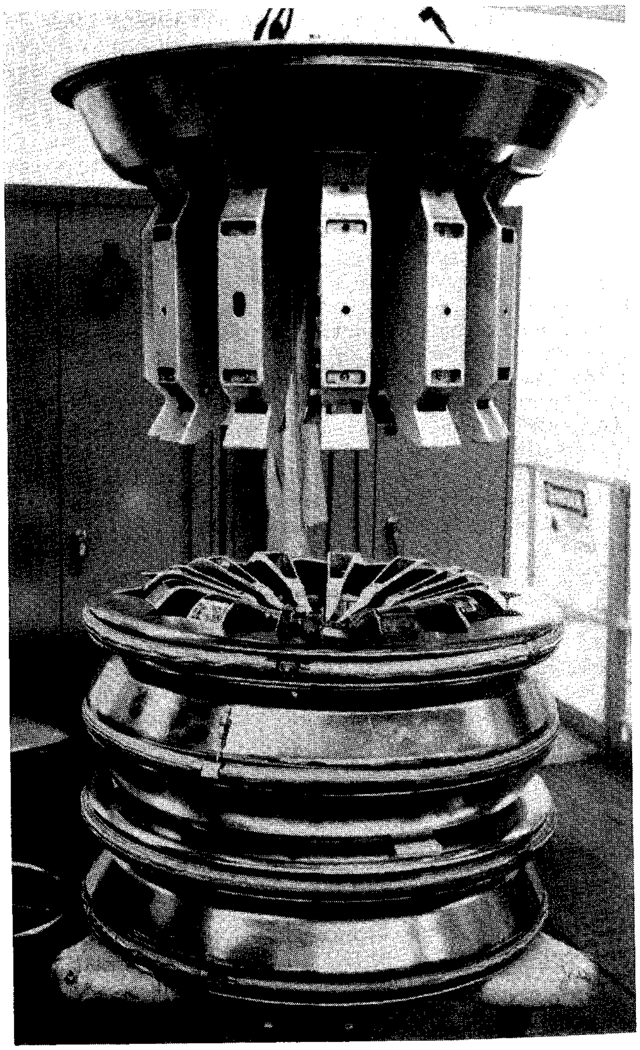

Figure 2. The vacuum feed assembly with the anode vertical MITLs extracted. The four horizontal disk feeds are shown.

after the large localized losses were eliminated, we used 4-chlorostyrene as a more sensitive indicator of electron losses. The plastic detector film was placed on several anode vertical MITLs. We found that the remaining losses were generally confined to the edges of the cathode vertical MITLs and, more importantly, to the inner vertical-to-disk convolute.

A more serious power flow problem occurs at the inner vertical-to-disk convolute. These losses were characterized by light global damage to the entire convolute region. As mentioned above, 4-chlorostyrene electron loss diagnostics indicated very severe losses in this region. When the vertical lines are tied together into a single horizontal disk-feed, the insulating magnetic field in the vertical lines (B_z) must assume an azimuthal configuration in the disk section. This transformation requires breaks and reconnections in the magnetic field lines. These transformations in the magnetic field are accompanied by local losses of magnetic insulation. Electron losses will occur only at locations where the local electric field is of sufficient strength to cause field emission of electrons and the local magnetic field is too weak to insulate the feed. When low or

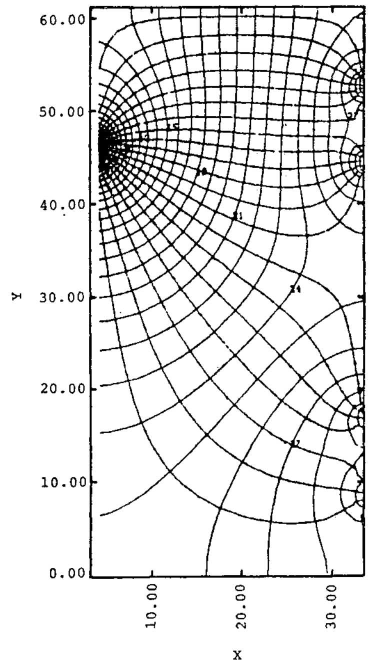

Figure 3. The vertical MITL modeled with four feed points and a single exit. The lines show tubes of equal conductance.

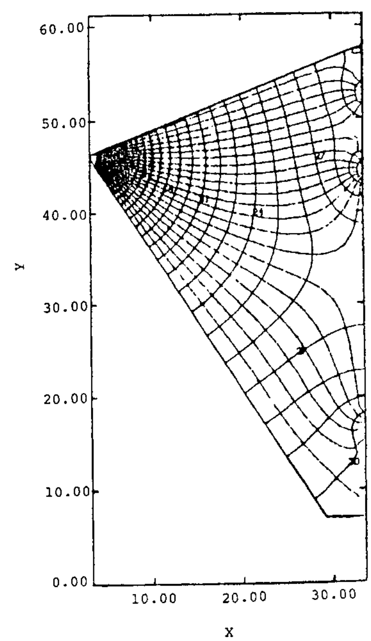

Figure 4. The first iteration of the cathode vertical MITL with realistic boundries.

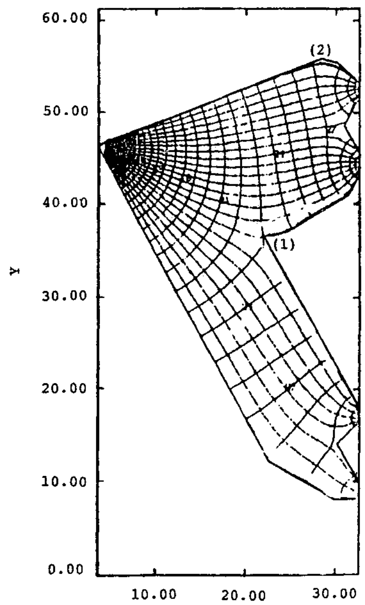

Figure 5. The final cathode vertical MITL design. The lines of equal conductance are supposed to be uniform in order to ensure good magnetic insulation.

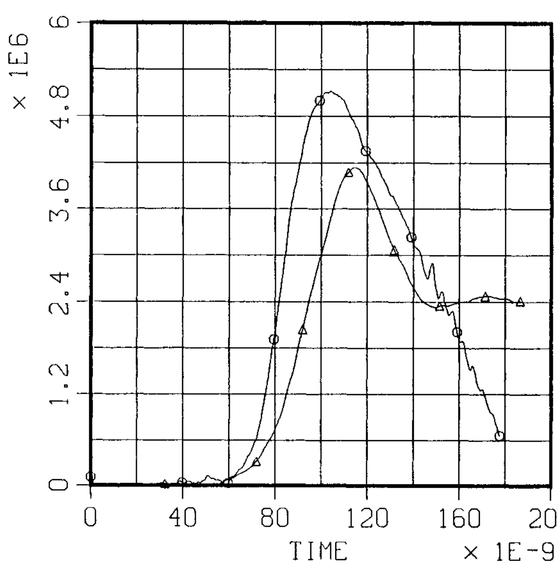

Figure 6. The current measured at the stack (circles) compared with the current near the load (triangles).

medium inductance short circuit shots were taken, no electron losses are observed because they produced higher currents (better magnetic insulation) and lower feed voltages (lower inductance and no dL/dt). This situation is quite different when a dynamic Z-pinch load is used. The higher initial inductance and the rapid increase in dL/dt forces the convolute to exceed the field emission limit and allows electron losses. The 4-chlorostyrene showed losses which increased toward the convolute. At the vertical-to-disk convolute the plastic was completely melted indicating losses greater than 10 kA/cm^2 (assumed 40 ns pulse). The current after the convolute was measured using calibrated cathode B-dots and quartz piezo-electric pressure transducers. For the majority of our data shots, the current losses amounted to one third of the total current and gave a reduction of 50% in the total x-ray yield. A comparison of the cathode B-dots and the insulator stack Rogowski coil waveforms is shown in Fig. 6. The losses are greatest at the peak applied voltage and then decrease after maximum current.

We made several hardware modifications to the convolute in attempts to reduce the losses. Welded current contacts between the vertical feeds and the disk feed, to reduce arcing and erosion, helped to decrease losses a small amount. Also, the joints between the vertical MITLs and the disk MITL were carefully smoothed. The cathode cone, the actual connection between the cathode vertical MITLs and the cathode disk MITL, was cut back to reduce potentially emissive surfaces. While these modifications seemed to help, no vast improvements in performance were seen.

Conclusion

We have developed a new vacuum convolute which consists of twenty four vertical MITLs coupled to a single disk feed. This vertical-to-disk convolute works well for short circuit loads where the voltage at the convolute is too low to induce electron emission. However, a gas puff Z-pinch load creates voltages large enough to produce significant electron losses at the convolute. The voltage at the convolute is strongly affected by the Z-pinch load parameters.

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